Weak Interactions in Neutron Stars

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Chapter 8

Summary and Conclusion

The description of neutron stars is a challenge in theoretical nuclear physics. Topics in this field are cooling of neutron stars, the effects of a magnetic field on it, the asymmetry in the neutrino emission and the bulk viscosity. These points are related to neutrino emission processes and processes with hyperons. The purpose of the research in this thesis is to improve the description of these processes and to look at the consequences for the topics that are mentioned above.

First the thermal evolution of a neutron star is considered, which is governed by weak neutrino emission processes. In a neutron star consisting of nucleons the one-body neutrino emission processes, such as the one-body neutrino-pair bremsstrahlung process and the direct Urca process, are generally forbidden. Therefore, the two-body neutrino emission processes, such as the two-body neutrino-pair bremsstrahlung process and the modified Urca process, are considered in the standard cooling scenario.

The standard cooling scenario of [Fri79] is based upon a nonrelativistic quasi-particle approximation and the use of the one-pion exchange potential. For a low neutrino energy (1 MeV) the two-body neutrino emission processes are directly related to the nucleon-nucleon scattering according to the Low theorem. In this thesis an on-shell T-matrix, which is based on experimental scattering between nucleons, is used to describe two-body neutral current NN bremsstrahlung (rather than OPE) as suggested by the low-energy theorem. The resulting rates for the two-body neutrino-pair bremsstrahlung process from neutrons are roughly a factor 4 smaller than those based upon OPE around neutron saturation density ($n_n \approx n_0$). We find that other medium effects are small: replacing the T-matrix by an in-medium G-matrix results in a relatively small effect of 20-30 percent; damping the infrared divergence (the so-called LPM effect for photon emission) in the medium has a negligible effect for low temperatures ($T < 5$ MeV); the relativistic effects are about 10 percent. Together the effects considered have noticeable influence on neutron star cooling dominated by the nn neutrino-pair bremsstrahlung process. These effects are also expected to affect the cooling behavior dominated by other neutrino emission processes.

Secondly, the effects of a magnetic field on the one-body neutral and charged current neutrino emission processes in neutron stars are considered. For the one-body neutrino-pair bremsstrahlung process the magnetic field creates the possibility of satisfying the conservation laws of energy and momentum by a spin-flip transition, because it causes different Fermi surfaces for different spin states. In the low density limit ($n_B \sim 0.15\ \mathrm{fm}^{-3}$), the one-body neutrino-pair bremsstrahlung process is comparable with the other neutrino emission processes at temperatures of a few times 10^9 K in combination with magnetic fields in the order of $10^{16} - 10^{17}$ G. For the direct Urca process it leads to a smearing of the transverse momenta of the charged particles by an amount $\sqrt{eB}$ due to the occupation of Landau levels. This smearing softens the triangular condition. Therefore, the process can already occur in magnetic fields of a few times 10^{17} G because of tunneling effects in the classically forbidden domain, where the triangular condition is not satisfied. The direct Urca process completely dominates for magnetic fields in excess of 10^{18} G. In the interior of the star this condition can possible be fulfilled. Hence, the investigation reveals that under certain conditions the one-body neutrino emission processes, the direct Urca and the one-body neutrino-pair bremsstrahlung process, compete with or dominate the commonly considered neutrino emission processes in the zero-field limit, such as the modified Urca process.

Thirdly, the anisotropic neutrino emission due to parity violation in the weak interaction is considered. In the nonrelativistic limit the neutrino-pair bremsstrahlung process is parity conserving. Therefore, it is unimportant. At about the highest surface magnetic field measured, $B = 10^{15}$ G, the direct and modified Urca process give recoil velocities of only a few km/s, which is much smaller than the observed velocities. The strength of the interior magnetic field of the neutron star can not be measured. The scalar virial theorem sets an upper limit of $B \approx 10^{18} - 10^{19}$ G. The recoil velocity due to the direct Urca process can amount to some thousands of km/s due to the higher polarization in a superstrong magnetic field, $B \approx 10^{18}$ G.

Finally, in the damping of neutron star pulsations and especially in the damping of r-modes, the bulk viscosity is relevant. In nuclear matter the bulk viscosity is determined by the previously mentioned direct and modified Urca process. Because of the small neutrino phase space of these processes, the weak nonleptonic hyperon processes dominate the bulk viscosity in matter with hyperons. Previously the contact interaction of $W^{\pm}$ exchange has been used to describe the weak nonleptonic hyperon processes in the bulk viscosity. In contrast, in weak Λ decays in large hypernuclei meson exchange is applied, which gives about the right order of magnitude compared to the experiments. In particular pion exchange in Born approximation is used to describe the weak nonleptonic hyperon processes in this thesis instead of the standard used contact interaction [Jon01, Hae02, Lin02]. Because of the use of OPE the $nnn\Lambda$ process can be included in the calculation for the bulk viscosity (the $nnn\Lambda$ process does not have a simple $W^{\pm}$ exchange contribution). Applying OPE the bulk viscosity is about 1-2 orders of magnitude smaller than that of the $W^{\pm}$ exchange. These results can be used for studying damping of pulsations and gravitational radiation driven instabilities in neutron stars.

Our understanding of neutron stars is not complete yet. Still many open questions are present. The research done in this thesis is a contribution to the improvement of our understanding of neutron stars.